LCA Case Studies

Functional Equivalence of Industrial Metal Cleaning Processes

Comparison of Metal Cleaning Processes Within LCA

Alexander Ruhland, Gabriel Striegel, Günter Kreisel

Institute of Technical and Environmental Chemistry, Friedrich-Schiller-University Jena, Lessingstraße 12, D-07743 Jena, Germany

Corresponding authors: Gabriel Striegel; e-mail: gabriel.striegel@gmx.de; Alexander Ruhland; e-mail: alex.ruhland@t-online.de

DOI: http://dx.doi.org/10.1065/lca2000.04.025

Preamble: Broadening the Environmental Toolbox

With a finalization of the primary LCA standards on the ISO level, it is about time to put more efforts into broadening the application and usability of the tool itself. One of the major principles is the examination of the entire life cycle of a product (or service) in order to ensure the system's perspectives and to identify or avoid environmental trade-offs. Thus far, such actions have been rather effective.

The LCA methodology can also be referred to as an applied system analysis. Thus, this methodology can be applied to systems which do not exactly describe a full life cycle for a product. Therefore, we may not consider such efforts to be exactly the same as LCA. However, the methodology and approach has proved to be of great value for such additional applications as demonstrated in the following paper. I personally believe that such an expansion of the methodology offers both new and exciting opportunities.

LCA studies are very often said to be of only little value within a decision making context, since such LCA studies are both time and resource intensive. Secondly, LCA studies are probably not always the most suitable perspective or tool for providing the right answers to the questions posed. I believe that an expansion of the LCA approach and methodology for multiple applications, including those which do not demand a full life cycle perspective, may show us a way out of our dilemma and attract new audiences and users for our LCA approach. Such a development in the form of an environmental system analysis and assessment toolbox is not only beneficial but even very necessary in order to avoid isolating the LCA community and to permit a growing number of applications for our tool. This makes our approach accessible to more organizations and, especially, also attractive to small and medium-sized enterprises which first want to start with their own core processes, i.e. within the framework of an EMS, EPE or other approaches, or for users of the methodology who are especially interested in process comparisons. Thus, tailored studies can pave the way to complete LCAs.

In addition, these more detailed process analyses open interesting opportunities for the LCA community. Today, most LCA studies are based on linear and descriptive data and process models. With more detailed process modeling, more realistic and suitable non-linear processes and simulation-like models can be derived. In this way, we can enrich our approach with the know-how from other disciplines and techniques, and consequently improve our tool even further.

We certainly should not forget the origin of our concept, the incorporation of systems as completely as possible, and all studies which only focus on pieces of the whole puzzle should clearly state this limitation. However, the methodology is too beneficial that it should not be used for multiple purposes. In my opinion, this is an important step towards the development of an integrated toolbox.

Dr. Konrad Saur, PE Product Engineering GmbH

Abstract. In an LCA case study, the three most frequent industrial metal cleaning technologies were assessed: Cleaning based on aqueous cleaning agents, non-halogenated hydrocarbon solvents and halogenated hydrocarbon solvents. Beside optimisation analysis, the comparison of the cleaning processes was a main goal of the study. The function of metal cleaning processes can be described with a set of parameters called functional parameters. In order to compare different cleaning processes within LCA, it is a precondition that all relevant functional parameters be equivalent. However, metal cleaning processes from different companies normally differ in most of the functional parameters and, thus, are not functionally equivalent. Therefore, it is necessary to calculate the material and energy flows of the processes corresponding to a reference function as a basis for comparison. This can be achieved by simulating the processes according to the functional parameters with the help of a process model. For a general comparison of the technologies, it is also necessary to consider the assessed machines having the same level of optimisation and the same scale.

Keywords: Case studies; empirical process simulation; function of a process; functional equivalence; functional unit; industrial metal cleaning; LCA methodology; optimisation of processes

Introduction

Cleaning and degreasing of products and intermediate products are important process steps in the metal processing and electric industry. Today the most frequent metal cleaning technologies are based on aqueous cleaning agents, non-halogenated hydrocarbon solvents, or halogenated hydrocarbon solvents. These three technologies have a market share of over 90% and can be used alternatively in many cases. In the study, "Integrated Assessment of Technologies of Industrial Component Cleaning and -Pretreatment" (BMBF, 1998), to which this paper refers, one goal was to compare the tech-

nologies with regard to their environmental impacts using LCA. The so-called foreground data was assessed on site in companies of the metal-processing industry by measuring the input and output flows of cleaning machines, whereas the background data, like the production of cleaning agents and energy, as well as the recycling and disposal processes, was mainly acquired from the literature. Altogether 4 machines of each technology were analysed in detail.

As a representative example of the analysed systems, a simplified life cycle of a metal cleaning process based on chlorinated hydrocarbons is shown in **Fig. 1**. All input and output flows of the cleaning processes were assessed over the whole life cycle with the exception of the parts to be cleaned. Their life cycle is independent from the cleaning process itself. In BMBF (1998), all process systems analysed are described in detail.

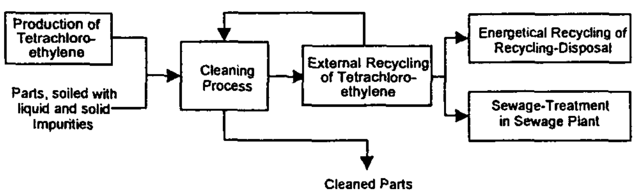

Fig. 1: Simplified life cycle of a metal cleaning process based on chlorinated hydrocarbons

As the function of metal cleaning processes proved to consist of several parameters, a primary task was to clearly define this function and find a suitable functional unit. Further, it was not possible to select cleaning processes having an equivalent function because the production situation and the specific products of companies vary in a wide range. Consequently, the cleaning processes could not be compared directly. To enable a comparison, nevertheless, we introduce an empirical process model that relates the material and energy flows to the parameters which describe the process function. When a general comparison of technologies on the basis of real machines is intended, additional problems arise due to different levels of optimisation and different machine scales. Therefore, the comparison of metal cleaning processes using LCA requires a reference base regarding the function of the process, the level of optimisation and the machine scale.

1 Functional Equivalence and Functional Unit of Industrial Metal Cleaning Processes

1.1 Function and functional unit

Defining the function of the analysed systems is an important part of the goal definition, especially within a comparative LCA (Fleischer and Schmidt, 1996). The function of a system results from its economic outputs, i.e. its products and services. Qualitative properties of products may additionally be part of the function. When a process is the centre of interest within LCA, not only the products of the process describe its function, but additional parameters as well, like the throughput of loads or the working time of a machine.

In the following we analyse a process of metal cleaning in order to derive the parameters that are relevant for defining the process function. In this case, the function of the process represents the function of the analysed life cycle. It should be mentioned that this paper does not deal with the problem to allocate environmental burdens to different economic outputs of the whole life cycle system.

Fig. 2 shows an industrial metal cleaning process embedded in the operational context of a company. In the centre of Fig. 2, the cleaning process and exemplary preceding and following processes are represented. The technical and operational boundary conditions, which influence the function of the metal cleaning process, are named. The directions of the arrows indicate the relationships between processes and boundary conditions.

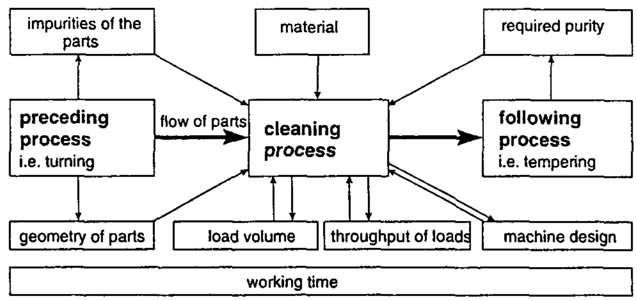

Fig. 2: Example of a cleaning process in an operational context

The function of metal cleaning processes was already discussed in previous studies (Spielmann and Sennhauser, 1994; Finkbeiner, Hoffmann and Kreisel, 1997; Fallot, 1997). However, the relationships represented in Fig. 2 were not entirely taken into account in these studies. According to Finkbeiner, Hoffmann and Kreisel (1997), the essential technical function of cleaning processes is to clean parts in such a way that certain qualitative and quantitative standards concerning surface properties and purity are met. The function comprises the geometry and the material of the parts to be cleaned, the quality and quantity of the impurities, and the required purity of the parts.

In addition to Finkbeiner, Hoffmann and Kreisel (1997), we also consider the time-related parameters "throughput of parts" and "working time of the cleaning machine" as a part of the function. From the point of view of the operational management, a degreasing machine with a high throughput of loads has a different function compared to one with a low throughput of loads, even if the resulting products are qualitatively the same.

Derived from these considerations we suggest the subsequent general definition of the function:

The function of a cleaning process is the cleaning of parts, respectively of loads of parts[1], within the following boundary conditions:

- The parts to be cleaned are of a certain form, a certain material composition and are soiled with certain impurities (liquid and/or solid) which are classified according to quality and quantity.

[1] The parts to be cleaned pass the machines in loads of a certain volume with a certain average amount of parts.

- The parts are cleaned in such a way that only a specific tolerated amount of impurities remains on the parts.
- A total daily throughput of parts is taken as a basis.
- The parts are cleaned during a certain daily working time.

Using this definition it is possible to identify a set of parameters which all together describe the function of cleaning processes (**Table 1**). In the following, these parameters are called "functional parameters". **Fig. 3** illustrates the multi-dimensional nature of the defined function qualitatively. As an example, two different functions of a metal cleaning process are shown.

Table 1: Important qualitative and quantitative parameters of cleaning processes

Reference	Designation	Symbol	Unit
Parts	Geometry and size of the parts	G	qualitative description
	material composition	M	qualitative description
Impurity	Quality of the impurities	Q	qualitative description
	Mass of impurities per load	i	g/load
Quality	Accepted remaining impurities per load	r	mg/load
Production	Daily working time	t	h/d
	Throughput of loads per hour	l	loads/h
	Load volume	Lv	m^3/load

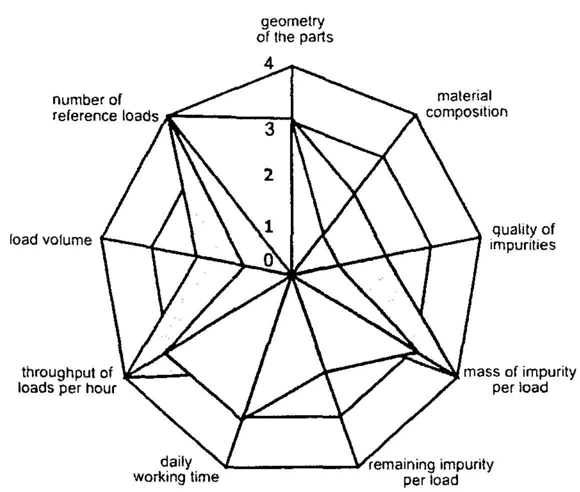

Fig. 3: Schematic representation of two different functions of a metal cleaning process

1.2 The Selection of the functional unit

The following are important properties of the functional unit as described in ISO 14041 (1999):

- The functional unit quantifies the function of the system.
- The functional unit provides a reference to which the input and output data are normalised.
- The functional unit should be clearly defined and measurable.

In the studies of Spielmann and Sennhauser (1994), Finkbeiner, Hoffmann and Kreisel (1997) and Fallot (1997), the following quantities are discussed as functional units for industrial metal cleaning processes:

- Mass of the parts put through,
- surface of the parts put through,
- mass of the removed impurities (liquid or liquid and solid),
- cleaning time,
- number of loads put through.

Finkbeiner, Hoffmann and Kreisel (1997) pointed out that none of these potential functional units describes the function as a whole. Each unit covers only a part of the function. According to our experience, in most cases it is not possible to accurately measure the mass or the surface of the parts put through for a representative period of time. Likewise, the mass of the removed impurities could not always be determined in a sufficiently precise way due to analytical problems. However, the number of loads put through is a clear and easily measurable quantity.

For this reason, we suggest one reference load (*RL*) put through as functional unit of metal cleaning processes. Cleaning processes are batch processes with the machines having a certain load volume. A reference load has a volume of 0.032 m^3, which is a commonly used load volume for cleaning machines. It contains a certain amount of parts depending on the geometry of the parts. Therefore, the reference load is directly proportional to the amount of cleaned parts. Since different load volumes (*LV*) are used in practice as well, the actual quantity of loads (*L*) has to be transformed to the number of reference loads (*RL*) by a factor *f* (Eq. 1 and 2):

$$f = \frac{0.032}{LV} \quad \left[\frac{m^3}{m^3}\right] \tag{1}$$

$$L = f \times RL \tag{2}$$

with: f = factor to transform the number of loads into the number of reference loads [dimensionless]
LV = load volume [m^3]
L = number of loads
RL = number of reference loads

The number of reference loads is a transparent and clearly defined functional unit that can be measured easily. It quantifies the function of the process. However, according to the definition of the function mentioned above, it is additionally necessary to describe the function with the help of the functional parameters. In order to compare cleaning processes, these functional parameters must be equivalent.

1.3 Functional equivalence by empirical process simulation

In industrial practice, metal cleaning processes typically show a wide variability in the functional parameters resulting from the specific product assortment of each company and different production situations. In the BMBF study (1998), great efforts were made in finding processes corresponding in the

functional parameters as far as possible. Likewise in other studies, more or less similar cleaning machines were selected and directly compared on the basis of a functional unit (i.e. SPIELMANN and SENNHAUSER, 1994; FINKBEINER, HOFFMANN and KREISEL 1997; FALLOT, 1997).

However, further analyses showed that the differences in some of the functional parameters cause significant differences in the energy and material flows of the systems. For instance, differences in the throughput of loads can lead to considerably different energy consumption per functional unit (**Fig. 4**). Therefore, it is not sufficient, to select similar processes.

To handle this problem, an empirical process model was developed that describes the relationships between the inputs and outputs of a metal cleaning process and the functional parameters. In this way it is possible to calculate the inputs and outputs for a reference function which is defined by a fixed set of functional parameters.

An important question in this context is, which of the functional parameters have a significant influence on the material and energy flows. Parameters with a negligible influence do not need to be included in the simulation model.

1.3.1 The empirical process model

Process analyses of metal cleaning machines and detailed measurements show that the annual mass and energy flows $\dot{F}j$ of a cleaning process mainly depend on:

- the number of loads put through,
- the mass of liquid impurities entering the machine,
- the working time of the machine and
- different operational periods[2] during machine operation.

In order to describe the relationships between the mass and energy flows per year, $\dot{F}j$ and the parameters mentioned above we found in the following linear Equation:

$$\dot{F}j = (k_{j1} \times \dot{L}) + (k_{j2} \times \dot{I}) - (k_{j3} \times \dot{T}) + (k_{j4} \times \dot{D}) \qquad (3)$$

with: $\dot{F}j$ = mass or energy flow j per year [kg/a or kWh/a]
$\dot{L}$ = number of loads per year [piece/a]
$\dot{I}$ = mass of liquid impurities per year [kg/a]
$\dot{T}$ = working time per year [h/a]
$\dot{D}$ = operational periods, expressed as working days per year [d/a]
$k_{j1} \ldots k_{j4}$ = coefficients, determined by measuring [different units]

Taking into account the quantitative functional parameters shown in Table 1, the annual material or energy flows $\dot{F}j$ can be transformed to material or energy flows per functional unit $\dot{F}j$, which is one reference load (Eq. 4).

$$\dot{F}_j = f \times \left(k_{j1} + k_{j2} \times i + k_{j3} \times \frac{1}{l} + k_{j4} \times \frac{1}{t} \times \frac{1}{l} \right) \qquad (4)$$[3]

Equation 4 calculates the inputs and outputs per functional unit [kg/RL or kWh/RL] depending on the functional parameters i (mass of impurities per load), l (throughput of loads per hour) and t (daily working time). The model can be applied to all cleaning processes analysed. The type of the material and energy flows $\dot{F}_j$ and the coefficients k_{jk} depend on the particular cleaning technology and machine. Consequently, the influence of individual functional parameters differs according to the machine and the technology.

However, we can draw some general conclusions concerning the functional parameters from Equation 4:

The material and energy flows per functional unit $\dot{F}_j$ are lower

- the fewer impurities per load enter the machine,
- the more loads per hour are put through, meaning the higher the capacity utilisation of the machine is, and
- the more hours per day the machine runs (the influence of starting and running after periods diminishes).

As an example, **Fig. 4** illustrates the influence of the throughput of loads on the current demand per functional unit. The graph is derived from Equation 4 with the coefficients (specific for the current demand) and functional parameters represented in Fig. 4. The coefficients refer to a cleaning machine that is based on halogenated hydrocarbons.

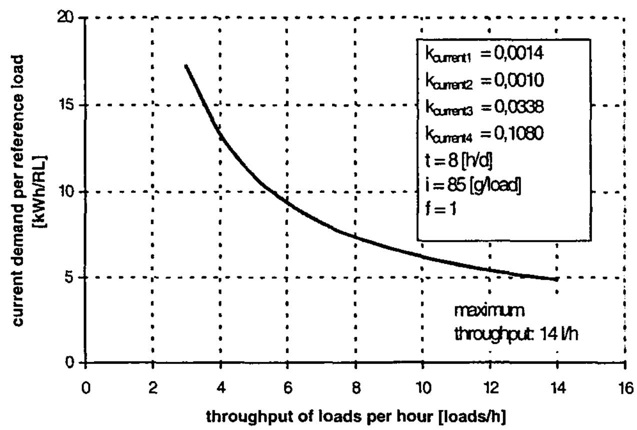

Fig. 4: Example for the influence of the throughput of loads per hour on the specific current demand of a cleaning machine (explanation of parameters see Table 1 and Eq. 4).

1.3.2 Determination of the coefficients

The unknown coefficients k_{jk}, which are specific for each machine and for each material or energy flow $\dot{F}_j$, must be determined in order to calculate Equation 4. Thus, Equation 3 is written in the form of Equation 5 by subdividing $\dot{F}_j$ to the shares $\dot{F}_{jk}$ (Eq. 5). The coefficients directly result from Equations 6 - 9:

[2] Operational periods are for instance the breaks, the time before and after running the machine. The material- and energy flows connected with a cleaning machine differ depending on the respective operational period.

[3] Mathematically, the throughput of loads per hour l and the daily running time t must not be zero, because then Equation 4 would not be explained. This case is, however, excluded for reasons of plausibility. The daily running time and the throughput of loads must be greater than zero, if any parts are cleaned at all.

$$\dot{F}_j = \dot{F}_{j1} + \dot{F}_{j2} + \dot{F}_{j3} + \dot{F}_{j4} \quad (5)$$

$$\dot{F}_{j1} = k_{j1} \times \dot{L} \quad (6)$$

$$\dot{F}_{j2} = k_{j2} \times \dot{I} \quad (7)$$

$$\dot{F}_{j3} = k_{j3} \times \dot{T} \quad (8)$$

$$\dot{F}_{j4} = k_{j4} \times \dot{D} \quad (9)$$

The shares $\dot{F}_{jk}$ as well as the parameters $\dot{L}$, $\dot{I}$, $\dot{T}$ and $\dot{D}$ are determined by measuring and analysing the physical and technical relations. Thus, the coefficients, k_{jk}, result directly from the Equations 6 – 9. In $\dot{F}_{j4}$ periodical shares of $\dot{F}_j$ are summarised which cannot be expressed by the parameters $\dot{L}$, $\dot{I}$ and $\dot{T}$. $\dot{F}_{j4}$ includes, for instance, machine specific quantities like the energy requirement during the daily starting and running after periods or the periodical exchange of cleaning solvents. These shares are modelled as a function of the number of working days.

As an example, the modelling of the current demand is explained: the total current demand of a machine is the sum of the current demand of the individual machine components. Each component is measured separately. From the resulting power-time graphs the relation between the current demand and the parameters $\dot{L}$, $\dot{I}$, $\dot{T}$ and $\dot{D}$ can be determined for each component. **Fig.** 5 illustrates a typical power-time graph of a machine component.

Fig. 5 shows a constant basic power demand during the daily working time overlaid by periodical peaks (refers to the left axis). The peaks result from the throughput of individual loads. Integrating the power demand leads to the energy consumption (right axis). The line on top shows the total energy demand of the component while the line on bottom represents the share, depending only on the working time. The share, depending on the number of loads, can be calculated as the difference between the two lines.

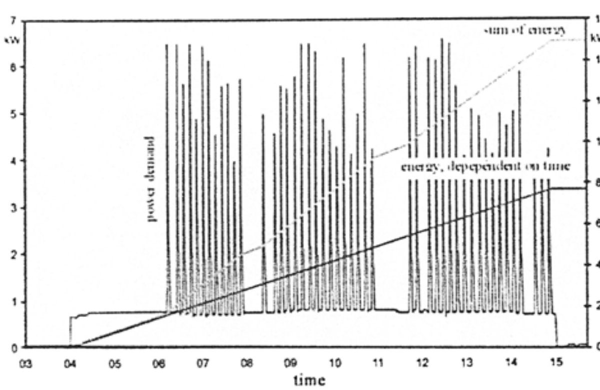

Fig. 5: Power - time graph of a machine component

1.3.3 Functional parameters not modelled

If functional parameters have no significant influence on the material and energy flows of processes, it is not necessary to integrate them into the process model. Likewise, it is not possible to simulate the material and energy flows if the technical relations are not known. In both cases, the processes to be compared should correspond as far as possible within these parameters.

For industrial metal cleaning we did not integrate the parameters *geometry and size of the parts, material composition* and *quality of the impurities* into the simulation model. These parameters do not show a relevant influence on the material and energy flows within a certain range. When selecting the processes to be compared, we paid attention to meet cleaning applications most similar in these parameters.

Furthermore, we did not integrate the parameter *accepted remaining impurities per load* in the model, because the relations between this parameter, and the material and energy flows, are rather complex and connected to the geometry of the parts and the quality of the impurities. Instead we defined a maximum value for the mass of remaining impurities per load as a threshold, which the assessed machines must meet. Otherwise, they are excluded from the comparison.

1.3.4 Why empirical process simulation

In this paper, we suggest an empirical model derived from measurements at machines working on site in companies. Alternatively, we could have proceeded from basic physical models using elementary physical values. For instance, the energy demand of a bath heating could be modelled with the help of the temperature, the container surface area, the heat transfer index, etc. However, detailed models of cleaning processes considering all relevant data do not exist to date. Moreover, the necessary expense of developing such models is much higher than empirical modelling, as also Spengler, Sieverdingbeck, Hähre and Rentz (1997) argued in the field of the metallurgical process industry.

With the help of the process model introduced here, the following main applications are possible:

- Calculating the inputs and outputs of metal cleaning processes with a set of functional parameters in order to compare different metal cleaning processes on the basis of a defined reference function.
- Calculating the inputs and outputs of metal cleaning processes that result from the variation of functional parameters in order to reveal the influence of single functional parameters in various scenarios (sensitivity analysis).

Unlike a simple input/output approach, this process model enables one to consider different reference functions and to check various optimisation potentials.

2 Equivalence of the Level of Optimisation

A general evaluation of alternative technologies does not only require an equivalent function, but also an equivalent level of optimisation relative to the machine technology and the operating conditions. Data gained from machines with different technical standards, or which are operating at different levels of optimisation, should not be compared.

A quantitative assessment of the level of optimisation regarding the technical standard or the operating management by indices is difficult, particularly if it is a question of a highly heterogeneous technology. Harsch et al. (1996) in-

troduce a proposal for a differentiated technical evaluation in the field of coating.

For this study, we selected only machines which were constructed within a certain range of years and which complied with the current legal regulations. In this way, we estimated the technical standard to be of a uniform level. However, machines operating on the basis of non-halogenated hydrocarbons represent a rather young technology compared to machines operating on the basis of aqueous cleaning agents or chlorinated hydrocarbons. This must be taken into account when interpreting the results.

With regard to the operational management of the machines, we estimated an equivalent level, as it must comply with the legal regulations and the technical guidelines of the manufacturer.

3 Equivalence of the Machine Scale

The capacity utilisation is defined as the actual throughput of loads per hour divided by its maximum value. It can be derived from **Fig. 4** that the capacity utilisation has a great influence on the results of the inventory of industrial metal cleaning systems. If a machine is designed for a throughput of loads bigger than operationally necessary, the capacity utilisation is low and, hence, the efficiency as well. In order to carry out a general comparison of cleaning technologies, it is necessary that the assessed machines have the same scale.

However, even after a careful selection of machines which are scaled as similar as possible, there are often differences in scale because of the variability of the market. In such cases, it is necessary to simulate an equivalent machine scale. This can be achieved by analysing the dimension of the machines followed by an arithmetical scaling to a fixed reference scale.

The maximum throughput of reference loads can be taken as a measure of the scale of a metal cleaning machine. In order to change the maximum throughput of reference loads, it is necessary to either vary the load volume of the machine or to vary the time period of a cleaning procedure. For the analysed cleaning processes, it can be assumed that the cleaning procedure itself stays constant. Hence, for varying the scale of a cleaning machine, a relation between the load volume and the material and energy flows is needed. For this we estimated a linear relationship, which is approximately valid within a certain range and has been confirmed by experts for all processes analysed.

In the course of a simulation, the machines to be compared are scaled up or down to a reference scale assuming a constant capacity utilisation (e.g. 100 percent). Because of the estimated simple linear relation between the material and energy flows and the load volume, Equation 4 can be applied using the maximum throughput of loads l_{max} of the machine instead of the actual throughput l (Eq. 10).

$$\dot{F}_{i,ref} = f \times \left(k_{j1} + k_{j2} \times i + k_{j3} \times \frac{1}{l_{max}} + k_{j4} \times \frac{1}{t} \times \frac{1}{l_{max}} \right) \qquad (10)$$

With Equation 10, the material and energy flows $\dot{F}_{i,ref}$ of a machine with a certain reference scale and a capacity utilisation of 100% can be calculated. However, in order to minimise errors caused by the estimation of a linear relationship, data should be assessed using machines whose scales are as uniform as possible.

4 Summary and Perspectives

For a comparison of cleaning processes, the function must be clearly defined and equivalent for all processes to be compared. The process of how to compare alternatively applicable cleaning processes is summarised in **Fig. 6**. The first step is to select cleaning machines which are able to carry out a cleaning task of interest. The machines should be able to fulfil the technical requirements and they should, to a certain degree, correspond in the functional parameters, the machine scale and the level of optimisation.

The second step is to carry out the inventory of the metal cleaning processes and to determine the coefficients k_{jk} of the introduced, empirical simulation model (Eq. 10). Then the functional parameters "mass of impurities per load", "throughput of loads per hour" and "daily working time" of the reference function are inserted in Equation 10 to calculate the inputs and outputs of the metal cleaning processes to be compared. After connecting the resulting inputs and outputs of the metal cleaning processes with the preceding and following processes of the life cycle, the whole metal cleaning life cycles can be calculated and compared.

The statistical validation of the introduced model would be desirable for further research, because the uncertainty of the model can not yet be quantified in detail. The possibilities to improve the scaling model used in this work should be analysed.

In the field of industrial metal cleaning it is especially remarkable that the various practices of machine use, described by the functional parameters, can cause greater differences in specific environmental effects than the different technologies. However, when the level of optimisation and the machine scale are similar and the process function is equivalent, the advantages and disadvantages of the individual technologies become visible. Due to the high demands on the flexibility of cleaning processes with regard to the possible throughput of parts and the cleaning tasks to be processed in future, another important point was that machines

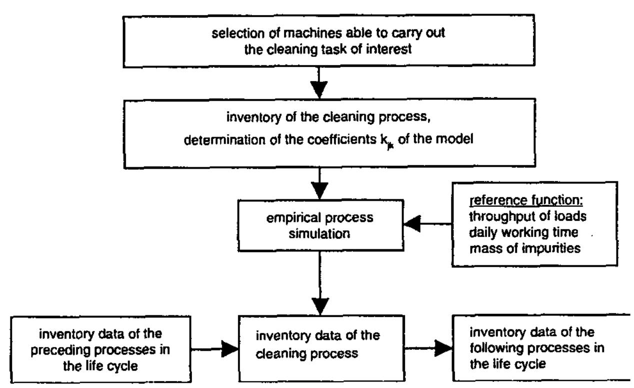

Fig. 6: Proceeding to compare different cleaning processes within LCA

are often chosen which offer a greater capacity than actually necessary. These excess capacities prevent the systems from running in an ecologically optimal manner [BMBF, 1998; STRIEGEL, HOFFMANN, KREISEL and GRÜN, 1999].

Although the analysis refers to alternative technologies of industrial metal cleaning, we think the introduced approach can be used for comparative LCAs of other processes as well.

Acknowledgements. We gratefully appreciate the generous support of the German Federal Ministry of Research and Development (BMBF) and the co-operation and contributions of our project partners Deutsche Gesellschaft für Galvano- und Oberflächentechnik (DGO) and Fraunhofer Institut für Verfahrenstechnik und Verpackung (Fh-IVV).

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Received: November 9th, 1999
Accepted: March 15th, 2000
Online-First: April 17th, 2000

Books

Life Cycle Assesment in Industry and Business:
Adoption Patterns, Applications and Implications

Authors: Paolo Frankl / Frieder Rubik
Publisher: Springer-Verlag (1999), ISBN 3-540-66469-6, DM 129,-

The challenge of our time is the greening of products. Different tools and concepts to support this process have been developed in the past decade. Among others, Life Cycle Assessment (LCA) appears as one of the most instructive management instruments for gaining insight into product-related environmental impacts and for supporting an effective integration of environmental aspects in business and economy.

Research on LCA was and still is focused on improving the methodology. In fact, the "LCA-technique" has significantly improved over the last few years. However, this research progress did nearly not stress the application context of LCA and its embodiment into business and industry. This is precisely the primary focus of the present book. Basing on the empirical information of a large survey and of twenty company case-studies, the book describes the set of applications and uses, as well as the dynamics of the adoption and integration patterns of LCA within business and industry. The resulting implications for research, business and environmental policy are also discussed.

Contents:

Introduction; Life Cycle Assessment; Objectives and Scope; Outline. – **Framework and Theoretical Background.** – **Application of LCA in General;** Methods; General Application; Years, Commissioning Bodies; Business as Clients; Subjects; Conclusions. – **A 'Static' Perspective on LCA Applications – Survey Results;** Method; Sample and Evaluation Procedure; Results; Conclusions. – **The Dynamics of LCA Adoption and Integration in the Firm – The Results of the Case Studies;** Introduction; Summary Reports of Selected Case Studies; Overview on Application Patterns; Conclusions. – **The Relationship Between Business and Policy: Expectations and Implications;** Business View on Policy; Policy View on Business; Conclusions. – **Conclusions and Recommendations;** Summarising Results; Interesting Results; Recommendations